

Citation for published version:

Molteni, E, Ferrari, M, Preatoni, E, Cimolin, V, Cerutti, S & Bianchi, AM 2011, Event related synchronization and Hilbert Huang transform in the study of motor adaptation: A comparison of methods. in *2011 5th International IEEE/EMBS Conference on Neural Engineering, NER 2011.*, 5910506, IEEE, Piscataway, NJ, pp. 132-135, 2011 5th International IEEE/EMBS Conference on Neural Engineering, NER 2011, April 27, 2011 - May 1, 2011, Cancun, Mexico, 1/01/11. <https://doi.org/10.1109/NER.2011.5910506>

DOI:

[10.1109/NER.2011.5910506](https://doi.org/10.1109/NER.2011.5910506)

Publication date:

2011

Document Version

Peer reviewed version

[Link to publication](#)

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Event Related Synchronization and Hilbert Huang Transform in the study of motor Adaptation: A Comparison of Methods

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Abstract—The study of neural correlates of motor execution is commonly performed by means of event-related processing of electroencephalographic (EEG) recordings, in which each event refers to a standardized, repeatable movement. Some authors have proposed a valuable single-parameter method, the Event-Related Synchronization and Desynchronization (ERS/ERD) approach, for the identification of motor-related power modulation in each EEG frequency band. Under evolving experimental conditions (such as learning or adaptation), though, the repetition of a motor scheme becomes time-variant, and the employment of single-parameter descriptors no longer represents the optimal choice. This occurrence is typically found in motor learning and adaptation studies. In this work we compared the performance of the ERS/ERD method with the multi-parametric Hilbert Huang Transform (HHT). Results confirmed the statistically significant equivalence of the two methods in providing indexes of neural synchronization and desynchronization. Moreover, HHT allowed the tracking of frequency shifts in the alpha and beta EEG bands. The two methods were tested on an EEG dataset recorded during a motor adaptation test.

I. INTRODUCTION

MOVEMENT EXECUTION usually induces motion-locked changes in the activity of pertaining neuronal populations, generally referred to as *event-related potentials* (ERPs). A longstanding tradition in neuromotor research has encouraged the extensive application of Event-Related Synchronization and Desynchronization (ERS/ERD) processing technique to motor ERPs [1]-[2]. Motion-locked modifications of neuroelectrical activity, indeed, very often consist of frequency-specific changes of the ongoing electroencephalographic activity and may result either in decreases or increases of power in given frequency bands, due to a concurrent decrease or an increase in synchrony of the underlying neuronal populations, respectively. The former case is called Event-Related Desynchronization (ERD) and the latter Event-Related Synchronization (ERS). Decades of research and the proliferation of a multitude of

applications have certified the repeatability, reliability and extreme handiness of ERS/ERD method. Moreover, the extraction of intuitive indexes such as the *maximum power decrease* or the *maximum power re-increase* in the beta frequency band (also called *beta-rebound*) promotes the combined use of ERS/ERD method with measures of motor performance and/or kinematics [2].

Despite the plurality of advantages, ERS/ERD bears also an unpleasant drawback: being this a single-parameter method, the signal frequency band has to be set *a priori*, and no adaptive criteria can be employed over time. For this reason, and under evolving investigational circumstances, the multi-parameters approach can provide some true advancement.

The Hilbert-Huang transform (HHT) method has an adaptive basis expansion, so that it can produce a real representation of data from nonlinear and non-stationary processes [3]. HHT is defined as the combination of the Hilbert spectral analysis (HAS) and the empirical mode decomposition (EMD). The key part of HHT is EMD, through which any data set can be decomposed into a finite number of intrinsic mode functions (IMFs). The instantaneous frequency defined using the Hilbert transform denotes the physical meaning of local phase change. As the decomposition is based on the local characteristics of the data, it is applicable to nonlinear and non-stationary processes [3]. Hence, this empirical method offers a tool for time-frequency-energy representations of the data.

Despite it is widely used in geophysical studies, the application of HHT in biomedical signal processing is recent, and only few authors have used it to process EEG signals [4][5]. In these studies, HHT is used for tracking alpha rhythm in the signal, while no tracking has ever been performed for the beta band. HHT algorithm is newer and less established than the ERD/ERS algorithm, but it attempts to overcome some limitations of the traditional method, allowing a bi-dimensional analysis based on the knowledge of the signal's power and frequency over time.

The aim of our study was to compare the ERD/ERS method with HHT, the former checking the presence of the expected evidences inside the data, and the latter exploring the potentialities of the tracking of frequency shifts. Both methods have been tested with data recorded during a motor adaptation task, which is an inherently time-adaptive phenomenon.

Manuscript submitted January 14, 2011.

The research was partially supported by the Dipartimento di Bioingegneria di Politecnico di Milano through the "Giovani Bioingegneri 2009" project and by the Regione Lombardia through the "New Italian Chilean Excellence" NICE project.

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II. MATERIALS AND METHODS

A. EEG and optoelectronic recordings

A 19-channel continuous EEG was recorded with Sam32 (MICROMED) amplifier, according to the International 10/20 system. A1 and A2 were used as reference with a midforehead placement of the ground electrode. Bipolar electrodes were used for the collection of eye movements (EOG). The A/D sampling rate was 1024 Hz. Upper limb movement analysis was also carried out using a 6-camera optoelectronic system with passive markers (SMART-E, BTS, Milan, Italy). Some kinematic indexes have been extracted for future investigation.

B. Protocol

The subjects were seated in front of a touch-screen monitor. The experiment consisted in 180 repetitions of pointing tasks. During each trial, the subject had to stare at a round cross-shaped cue sign first. This sign was meant to give advanced warn of the reaching point (*planning* stage). The subject was instructed not to move at this stage, and to wait till a full circle (target) appeared in the same position. The subject had to touch the centre of the target with the tip of a wand, whose dimension and positioning had been designed to substitute the right forefinger (*execution* stage). The interval between cue and target signs was randomized between 1.5 and 2.0 s in order to avoid movement anticipation. After movement execution, feedback information about performance was given in the form of a red point indicated the point touched together with a percentage value based on the closeness of planned and executed touches. At the end of this step, the new trial begun. The task was made up of 3 sessions (*adaptation* stage) of 60 trials each (15 repetitions for each of the 4 possible targets, randomly repeated). The right wrist motion was altered by an elastic band fixed to an external support. Bands with different elasticity coefficients were employed in the three sessions, in order to reiterate the adaptation request. Standardized instructions were administered.

C. Data analysis

Electroencephalographic (EEG) data were digitally offline filtered with a band pass finite impulse response (FIR) filter (0.5–45 Hz) to remove noises and muscular artifacts. Then they were cleaned up from ocular artifacts by means of independent component analysis (ICA) algorithm implemented in EEGLab toolbox [6] and downsampled at 100 Hz. Cleaned EEG signal from C4 electrode position (corresponding to the motor area contralateral to the movement) was selected for each subject, and then processed by means of (i) the standard Event Related Synchronization /Desynchronization (ERS/ERD) method [2] and (ii) an optimized version of the Empirical Mode

Decomposition based Hilbert-Huang transformation method (EMD-HHT) [3], purposely engineered for the investigation of alpha and beta EEG rhythms. EEG power tracks obtained through the employment of the two methods were comparatively validated. Furthermore, EMD-HHT allowed the tracking of power peaks frequency shifts.

The Event Related Synchronization (ERS) method

After artifact removal, EEG data were digitally re-filtered with a band pass FIR filter in two different frequency bands (alpha 7-13 Hz and beta 13-25 Hz). Filtered EEG data were exported in MATLAB environment, epoched into non-overlapping segments of 2.0 s duration (-0.5 to 1.5 s) relative to cue presentation and into periods of 7.5 s duration (-2.5 to 5.0 s) relative to target presentation. The baseline period was taken before the beginning of each trial (-3.5 to -2.5 s before the target onset). Then, the rhythm synchronization (ERS) and desynchronization (ERD) were evaluated, in order to highlight variations in the EEG frequency content with respect to the baseline period. This was done according to the following expression:

$$\Delta P_j(i) = \frac{P_j(i) - P_{Rj}}{P_{Rj}} \times 100 \quad (1)$$

where $P_j(i)$ is the current power value in the j band, and P_{Rj} is the average power in the same band, calculated during the baseline condition [2]. In order to study the effects of task repetition, and thus adaptation, epochs were averaged separately (i) for the first, second and third sessions and (ii) for the first (trials 1 to 20 - *early* adaptation), central (trials 21 to 40 - *intermediate* adaptation) and last trials (trials 41 to 60 - *late* adaptation) of each session. Before the averaging processes were performed, all the EEG epochs relative to target presentation were normalized for the duration of the pointing movement and resampled between arbitrary time points 0 and 1: a rescaling of the data with respect to the end of movement was then obtained.

The Empirical Mode Decomposition based Hilbert-Huang transformation method (EMD-HHT)

Before performing the Hilbert spectral analysis, an Empirical Mode Decomposition (EMD) method was applied to EEG data, since these latter cover a broad frequency band and single rhythms need to be isolated. EEG data were epoched with respect to cue and target presentation as described in the previous section. Epochs were digitally filtered with an adaptive band pass Parks-McClellan FIR filter in two different frequency bands: alpha and beta. The center frequency ω_c of the bandpass of the filter could range between 7 and 13 Hz for the alpha rhythm and between 13

and 25 Hz for the beta rhythm. Initialization was done manually. The lower and higher cutoff frequencies of the adaptive passband were at $\omega_L=(\omega_c-3)$ Hz and $\omega_H=(\omega_c+3)$ Hz respectively. The EMD, was applied to alpha and beta EEG data as proposed in [3] in order to identify all extrema of the signal $x(t)$; interpolations between minima (and between maxima) were performed, ending up with some envelopes $e_{\min}(t)$ and $e_{\max}(t)$. The mean $m(t)$ was computed between the two envelopes, and the detail (also called Intrinsic Mode Function – IMF)

$$d(t) = x(t) - m(t) \quad (2)$$

was iteratively calculated, until it could be considered as zero-mean according to the stopping criterion (see [3]). The window length of the EMD calculation was as short as 32 samples for the alpha rhythm and as 20 samples for beta. Having obtained the IMFs using EMD method, the Hilbert transform was applied to the first IMF component $c_1(t)$.

The local instantaneous energy $IE(t)$ was calculated for both alpha (α) and beta (β) bands:

$$IE_{\alpha}(t) = \int_{\omega_{\alpha L}}^{\omega_{\alpha H}} H_{\alpha}^2(\omega, t) d\omega \quad (3)$$

$$IE_{\beta}(t) = \int_{\omega_{\beta L}}^{\omega_{\beta H}} H_{\beta}^2(\omega, t) d\omega \quad (4)$$

Where H is the “Hilbert transform”, ω is the investigated frequency and t represents time.

The tracking of frequency shifts of EEG power peaks along time was performed through (5):

$$\theta_1(t) = \arctan(H[c_1(t)] / c_1(t)) \quad (5)$$

where $c_1(t)$ is the first IMF. As the tracking window introduced some delay, frequency shifts diagrams were realigned with a postponement of 16 samples in the case of alpha rhythm and of 10 samples in the case of beta rhythm.

D. Index identification

For both the algorithms presented above, selected parameters were identified and calculated in each frequency band, subject, trial and session:

- ERS: maximum amplitude of the power increase;
- ERD: maximum amplitude of the power decrease;
- ERS-ERD: difference between maximum synchronization and desynchronization amplitudes.

Pearson’s correlation has been calculated between the same indexes, obtained by means of the two different methods.

E. Subjects

Nine healthy subjects (7 males and 2 females) volunteered in the study. Their mean age was 24 years (SD 3.20, range 20–29). All participants were strongly right-handed according to the Edinburgh Handedness questionnaire. The study was approved by the local Institutional Review Board. Written informed consent was obtained from each subject, strictly

before the beginning of the experiment, after the examination and test procedure had been explained.

III. RESULTS AND DISCUSSION

In this work we separately studied planning and execution phases of movement. Planning was investigated in the alpha while execution was evaluated in the beta frequency band.

A. ERD/ERS results

A power decrease about 1 s after cue presentation was observed in the alpha band (fig.1), maximally evident over the left centro-parietal electrode sites. Through the three sessions, some variability was highlighted in the maximum amplitude of the synchronization increase and desynchronization decrease. This evidence was most prominent in the comparison of the early (blue) and intermediate (red) sessions of adaptation.

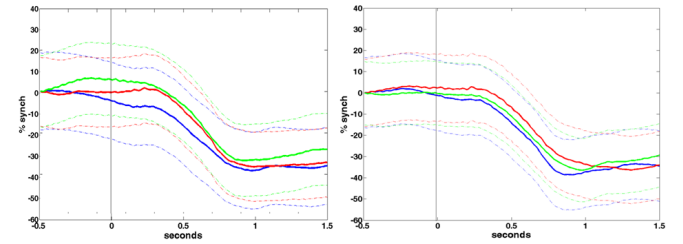


Fig. 1- Power changes after CUE onset (ERD/ERS results), comparison between sessions (left panel: blue=first; red=second; green=third session) and adaptation stages (right panel: blue=early; red=intermediate; green=late stage). Standard deviations in dashed lines.

The execution phase of the pointing task provided interesting results in beta frequency range, in which a power decrease always accompanied movement execution, until beyond task offset; then a rebound followed (fig.2). Both through sessions and adaptation-stages, an increase of the maximum rebound and some anticipation was found, though not significant. Indeed a decrease of the interval duration between the peak of synchronization and the end of the movement execution emerged.

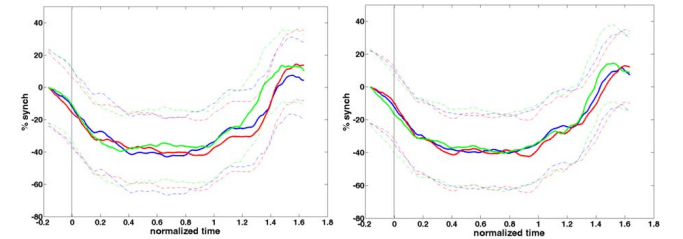


Fig. 2- Power changes after TARGET onset (ERD/ERS results), comparison between sessions (left panel) and adaptation stages (right panel).

B. Hilbert-Huang results

The employment of the HHT method provided motor patterns in the alpha (fig.3) and beta bands (fig.4) extremely similar to those extracted by means of the ERS/ERD method.

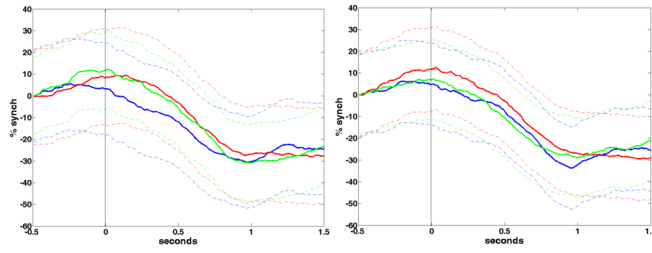


Fig. 3- Power changes after CUE onset (HHT results), comparison between sessions (left panel) and adaptation stages (right panel).

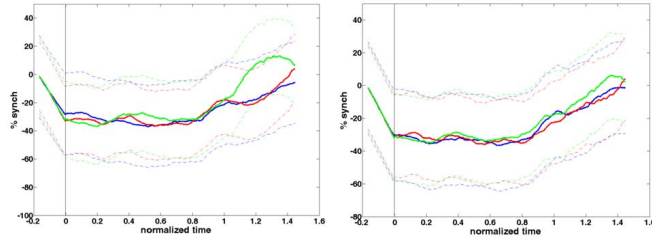


Fig. 4- Power changes after TARGET onset (HHT results), comparison between sessions (left panel) and adaptation stages (right panel).

HHT also allowed the extraction of information about adaptation-related shifts of the fundamental frequencies in the alpha and beta bands (fig.5). For the planning phase, a decrease of the frequency variability between the first and the late session was found. A phase-shift between the results of the first session (blue) with respect to the results found in the other two sessions was also disclosed. In contrast, during execution phase, an increase in frequency variability was found, proceeding with session execution. Frequency shifts could be related to the managing of the motor scheme in the brain, but further investigation needs to be done.

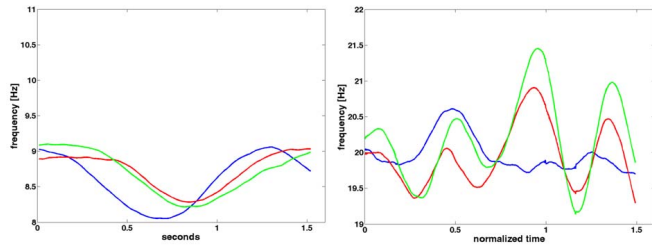


Fig. 5- Frequency changes after CUE onset (left panel) and after TARGET onset (right panel).

C. Comparison of methods

The indexes presented above were evaluated for all the three sessions and stages of the protocol. A correlation study was carried out in order to compare the output calculated by both the methods presented above. A correlation was found for all the parameters selected (tab.1), proving the complete equivalence of the two. Hilbert Huang Transform, though, provided some further information about dynamic frequency shifts of EEG bands.

TABLE I
CORRELATION BETWEEN NEURONAL MEASURES

	rho	p-value
ERSbeta (*)	0,8076	0,0000
ERDbeta (*)	0,887	0,0000
ERSalpha (*)	0,4876	0,0000
ERDalpba (*)	0,6403	0,0000
ERS-ERDbeta (*)	0,629	0,0000
ERS-ERDalpba (*)	0,5819	0,0000
m_s_ERSbeta (*)	0,8113	0,0000
m_s_ERDbeta (*)	0,8323	0,0000
m_s_ERSalpha (*)	0,5641	0,0022
m_s_ERDalpba (*)	0,741	0,0000
m_s_ERS-ERDbeta (*)	0,4775	0,0118
m_s_ERS-ERDalpba (*)	0,7685	0,0000
m_p_ERSbeta (*)	0,8198	0,0000
m_p_ERDbeta (*)	0,9165	0,0000
m_p_ERSalpha (*)	0,5782	0,0016
m_p_ERDalpba (*)	0,7239	0,0000
m_p_ERS-ERDbeta (*)	0,4384	0,0222
m_p_ERS-ERDalpba (*)	0,8176	0,0000

(*) indicates values which were considered statistically significant; m_s indicates protocol sessions; m_p indicates adaptation stages.

IV. CONCLUSION

This study aimed to compare the performance of two different EEG signal processing methods in a motor adaptation study: ERD/ERS and HHT methods. These two techniques showed comparable results, proving their equivalence. In addition, HHT method provides additional information, opening a new door on the investigation of shifts in the fundamental frequency during motor execution, being worth the perceivable increase in the computational cost during processing phase.

V. ACKNOWLEDGMENT

The authors are grateful to Manuela Galli and Renato Rodano for their useful suggestions concerning the protocol establishment and validation.

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